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ARO, Inc.

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VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
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ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

LOW-DENSITY BOUNDARY-LAYER MODULATION BY SUCTION IN A HYPERSONIC NOZZLE

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FOREWORD

The research reported herein was conducted at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 65802F.

The results presented herein were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. This work was conducted from June 8, 1970, to June 30, 1972, under ARO Project Nos. VT0089, VT5174, and VM0175. The manuscript was submitted for publication on September 8, 1972.

This technical report has been reviewed and is approved.

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ABSTRACT

The potential value of controlled boundary-layer removal from the wall of a nozzle for low-density hypersonic flow was investigated in a brief experimental program. A particular objective was the achievement of sufficient control over boundary-layer thickness to enable a contoured "design-point" nozzle to be operated under off-design conditions without excessive deterioration of flow uniformity. The conditions of flow were such that the nozzle contour was greatly influenced by boundary-layer thickness. The manner of boundary-layer fluid removal involved suction through perforated walls by utilization of the naturally available pressure ratio existing where local nozzle static pressures exceeded the pressure in the large tank which enclosed the nozzle and test section. Even though mass flux removed was a small percentage of total nozzle mass flux, there was an adverse effect on flow uniformity with no significant gain in flexibility of usable operating conditions. Although there is no doubt that the flow may be influenced, it does not appear easy to gain sufficient control over the boundary layer without creating unacceptable disturbances to the test section flow. Some possibilities for gaining boundary-layer control are briefly discussed, but their merits are uncertain. It is obvious that the boundary layer can be removed, but the quality and level of control of the resulting test section flow that can be had for reasonable cost are not equally clear.

CONTENTS

APPENDIXES

NOMENCLATURE

A^*	Nozzle throat area
c_d	Discharge coefficient
d	Nozzle diameter
h	Enthalpy
M	Mach number

$\dot{m}$	Mass flux
$\dot{m}_t$	Total mass flux through A^*
p	Pressure
q	Dynamic pressure
Re	Reynolds number (Re_2 = value downstream of normal shock)
r_w	Nozzle wall radius
S	Molecular speed ratio
T, $\overline{T}$	Temperature
U	Flow velocity
x, R	Nozzle axial and radial coordinates, respectively
δ	Boundary-layer thickness
δ^*	Boundary-layer displacement thickness
θ	Boundary-layer momentum thickness
λ	Mean free path
ρ	Density

SUBSCRIPTS

1, 2	Suction plenum chambers
o	Total, reservoir conditions
t	Tank
w	Nozzle wall condition
∞	Free-stream condition

SUPERSCRIPT

'	Impact pressure

SECTION I
INTRODUCTION

The advent of hypersonic wind tunnels designed for aerodynamic testing of models in the flight range corresponding to altitudes above 40 miles has introduced the requirement for nozzles that produce flows with negligible axial and radial gradients in the test region when very thick boundary layers exist on the nozzle walls. Because these nozzle flows are strongly responsive to boundary-layer thickness, and boundary-layer thickness is determined by Reynolds number, Mach number, and wall temperature ratio as well as geometric parameters, nozzles that are "contoured" to produce uniform test region flows are necessarily designed for a single operating condition. When $\delta \ll r_w$, as in conventional wind tunnels producing large Reynolds numbers, the unit Reynolds number may be varied over a wide range, usually by varying reservoir pressure. When $\delta \ll r_w$, the changes in δ accompanying changes in reservoir pressure cause negligible off-design perturbations to the inviscid core flow, but when $\delta = 0(r_w)$, off-design conditions with acceptable core flow uniformity are severly limited.

In this report the merits of a particular technique for reducing the thickness of the boundary layer in a nozzle by venting sections of the nozzle to naturally occurring lower pressure "suction" regions are briefly explored. Applicability of the technique for the control of the nozzle exit conditions in a Mach 12 contoured nozzle has been investigated in a wind tunnel wherein the nozzle extends into a tank as shown in Fig. 1 (Appendix I). Static pressures in the upstream portions of the nozzle are greater than the tank pressure ($p_w > p_t$). Thus, by venting the nozzle where $p_w > p_t$, a "naturally available" suction is applied. Mass flux may be controlled by varying either suction area or pressure differential, or both. Even though the mass flux vented still must be passed through the diffuser and pumping system of the wind tunnel, the potential controllability of the nozzle boundary layer is well worth investigation. If the method were to allow even modest variation of reservoir conditions without significant sacrifice of uniformity in the core flow, it would repay the effort. However, if the mass removal cannot be accomplished without introducing flow disturbances in the test section, then it is not an acceptable technique.

SECTION II
APPARATUS

2.1 TUNNEL M

The Low Density Hypersonic Wind Tunnel (M), shown photographically in Fig. 2a and schematically in Fig. 2b, is a continuous, arc-heated tunnel in which nitrogen is normally used as the test gas. Pumping is provided by three stages of air ejectors in series which exhaust into the VKF main compressor system through the VKF Tunnel C test section. This arrangement permits simultaneous operation of these two tunnels, or either can be operated alone. Tunnel M consists basically of the following major components, in streamwise order:

1. Rotating arc-type d-c heater with a power supply rated at 200 kw for continuous operation. Gas is injected into the arc heater in a swirl mode.
2. Clyindrical settling chamber of 3.8-cm diameter and 7.6-cm length.
3. For the present study, an axisymmetric, contoured, aerodynamic Mach 12 nozzle. The nozzle wall was perforated as shown in Fig. 3, and two modes of operation were used: (a) suction, when orifices "A" were open, and (b) no net suction, when orifices "A" were closed.
4. Stationary bulkhead of 2.4-m diameter, which supports the nozzle, probe drive and support unit, and pressure-measuring system. The bulkhead contains eight 30.5-cm-diam ports.
5. Clyindrical 2.4-m-diam test chamber which moves downstream to allow access to the test section, models, and probes.
6. Axisymmetric diffuser with convergent entrance, constant area throat, and divergent outlet. Interchangeable units are available for different test configurations.
7. Downstream heat exchanger.
8. First air-ejector stage.
9. Isolation valve.

2.2 HYPERSONIC NOZZLE DESIGN

The method of design for the two axisymmetric contoured nozzles of Tunnel M has been described previously by Potter and Carden (Ref. 1). These nozzles provide uniform flows of nitrogen at nominal Mach numbers of 12 and 18. An inviscid expansion core of flow is calculated by the method of characteristics, and the displacement boundary-layer thickness distribution calculated by the method of Cohen and Reshotko (Ref. 2), with correction for transverse curvature, is combined with the expansion core to give the nozzle wall coordinates.

In order to facilitate boundary-layer removal, two porous nozzle sections were fabricated for the Mach 12 nozzle: Section 1 with 1947 3.18-mm-diam holes and Section 2 with 2493 3.18-mm-diam holes (Fig. 3). The suction sections were located in a region of the nozzle from which Mach waves would project downstream through the test section. Perforations existed between stations $14 < x < 26$ in. ($36 < x < 65$ cm).

2.3 NOZZLE FLOW CONDITIONS

Nozzle free-stream conditions are determined by continuous measurements of free-stream stagnation pressure, stilling chamber pressure, and tunnel mass-flow rate. The basic assumption of the flow calibration, confirmed a posteriori, is that thermodynamic equilibrium exists in the tunnel stilling chamber and that the gas becomes frozen in its vibrational mode at the nozzle sonic area. Using the measured nozzle discharge coefficient, p_o, $\dot{m}$, and A^* and real-gas nitrogen thermodynamic properties, inferred values of T_o are calculated. The gas is assumed to behave as a perfect gas downstream of the throat, and perfect-gas relationships are employed to arrive at free-stream flow properties. Measurements using local and total calorimeters, mass-flux probes, and nozzle wall static pressure measurements have confirmed the validity of the flow calibration procedures. Measured impact pressures are corrected for errors induced by probe viscous effects and the influence of energy flux into the probe orifice common to pressure measurements in low-density, hypersonic wind tunnels (Ref. 3).

2.4 TUNNEL INSTRUMENTATION AND DATA ACQUISITION SYSTEM

In addition to instrumentation necessary to monitor the arc heater and stilling chamber conditions, the following instrumentation is available in Tunnel M:

1. A low pressure level (3 to 30 mm Hg full scale) primary standard pressure transducer system located within the tunnel test chamber.
2. A thermocouple system using Chromel®-Alumel® thermocouples for surface temperature measurements.

Pressure probe location is varied by remotely controlled drive mechanisms and monitored by linear potentiometers.

Data are recorded on the VKF Beckman 210 high-speed analog-to-digital data acquisition system, which scans all channels in about 1 sec and records data on paper tape. These raw data are then put into the VKF CDC 1604B computer for data reduction. Data are also plotted on-line by mechanical plotters for quick analysis.

SECTION III
RESULTS AND DISCUSSION

3.1 NOZZLE WITH NO MASS REMOVAL

The nozzle was first operated at its design condition, i.e., $p_o = 1.95 \times 10^6$ N/m^2, with no suction. The flow properties for this condition are given in Table I (Appendix II). Radial impact pressure surveys were taken at distances of 0, 25.4, and 50.8 cm upstream of the nozzle exit plane. As shown in Fig. 4, the uniform core flow region was approximately 8 cm in diameter. An off-design condition, $p_o = 1.64 \times 10^6$ N/m^2, with no suction was investigated, and the impact pressure surveys are presented in Fig. 5. Table II gives the flow conditions at the nozzle exit. Both conditions are acceptable for work with long models, inasmuch as the axial length of near-uniform flow is far greater than that required for typical model configurations. The boundary-layer displacement thicknesses, δ^*, obviously were computed satisfactorily in view of the Mach number's being near the design value throughout the test section, as indicated by the continuous centerline survey.

It is worthy of note, however, that the boundary-layer total thickness, δ, was found to be greater than computed. This was due in part to the fact that the average nozzle wall temperature, $\overline{T_w}$, was greater than the value assumed in computing the nozzle boundary-layer thicknesses. Taking, for the hypersonic region of the nozzle,

$$\overline{T_w} = (T_1 + T_2 + T_3)/3$$

one obtains $\overline{T}_w$ = 390°K for the design condition with no suction. Nozzle wall backside cooling by water existed for x < 15 cm, but no water cooling was applied for $x \geq 15$ cm. During the designing of the basic nozzle, it was assumed that $\overline{T}_w$ = 300°K, but the cooling downstream of the suction areas was later omitted for simplicity of fabrication.

On the basis of Refs. 1 and 2, it is estimated that this change of average wall temperature would not affect momentum thickness, θ, appreciably. However, the increased $\overline{T}_w$ in the hypersonic part of the nozzle would cause θ/δ to decrease or δ to increase by 6 to 7 percent. Similarly, Ref. 2 predicts a 2- to 3-percent increase of δ^*/δ. Thus, the increased $\overline{T}_w$ above the value assumed during design of the nozzle probably accounts for δ^* being slightly greater than computed, i.e., the Mach number's being 11.8 instead of the design value of 12. Momentum thickness was not measured in this experiment, but δ^* is obtainable on the basis of the one-dimensional flow area expansion ratio required to reach the exit Mach number, and δ is taken from the impact pressure surveys.

In the Cohen and Reshotko method (Ref. 2), which is the basis for these calculations, one determines δ^* as a multiple of the previously calculated δ. The present experimental result gives a ratio of δ^*/δ smaller than that computed by the method of Ref. 2. A similar situation is shown in Table I of Ref. 1. Those data are combined with the present data in Table III which indicates that under the four cold-wall ($T_o \gg T_w$) hypersonic flow conditions

$$\frac{(\delta^*/\delta)\ \text{experimental}}{(\delta^*/\delta)\ \text{calc. by Ref. 2}} \simeq 3/4 \quad .$$

or

$$\delta\ \text{experimental} \simeq (4/3)\ \delta\ \text{calculated by Ref. 2.}$$

It must be noted that the conditions of these nozzle flows where $\delta = 0(r_w)$ are rather extreme for the application of the method of Ref. 2, and it is not intended to imply that the result expressed above is general. Because both $\overline{T}_w/T_o$ and $(\delta\ \exp/r_w)_{exit}$ vary in the data of Table III, it is not clear if the apparent error in computing δ is related to one or both of those factors.

To minimize expense of fabricating the nozzle for these experiments, the no-suction configuration included the 0.32-cm holes in the nozzle wall. There was not a separate test of a smooth-walled nozzle; the large orifices "A" in the outer cylindrical shell of the suction manifold simply were sealed to create the no-suction case. Therefore, it must be assumed that some degree of disturbance emanated from the porous section, even at zero net mass flux, owing to the probable recirculation of flow and the rough wall caused by the numerous small holes. This may be the reason for the small-scale nonuniformity of the impact pressure profiles at x = 56.3 in. seen in Figs. 4 and 5 and could have had an effect on boundary-layer thickness.

3.2 NOZZLE WITH MASS REMOVAL

The surveys for full suction, i.e., for both Sections 1 and 2 fully open, are shown in Fig. 6. For this case, there was no apparent improvement in diameter of the nozzle exit core flow. Figures 7 through 12 depict various combinations of suction with Sections 1 and 2 opened or closed. An off-design nozzle condition also is represented. Table IV summarizes the major quantities pertaining to the suction cases. It is seen that the mass flux withdrawn from the boundary layer varied from zero to a maximum of (0.0019 + 0.0012)/0.071 = 0.044 = 4.4 % of the total mass flux for full suction at the design condition. Thus, the test section conditions remained essentially unchanged regardless of the suction rate.

To calculate the mass flux through the perforated areas, it is permissible to use the equation for choked flow. Figure 13 and Table IV show that sonic flow conditions may be assumed in either the small holes in the nozzle wall or the larger orifices "A". Because greater confidence can be placed in a calculation based on orifices "A", the mass flux was computed on the basis of the pressures p_1, p_2, p_t, the temperature of gas in the plenum chambers of the orifices, and the geometric orifice area. The Reynolds numbers representing the flow are low enough that a discharge coefficient less than unity is applicable. An iterative calculation led to an estimate of c_d = 0.6, based on Ref. 4, and that value was used in calculating $\dot{m}_1$ and $\dot{m}_2$. Basic nozzle calibration includes the measurement of m_t, mass flux through the nozzle throat.

Since time did not permit the investigation of other nozzle and suction flow conditions, a full appreciation of the flexibility or other poten-

tial advantages of the "natural" suction scheme has not been gained. However, the results obtained to this point are not encouraging. As a tentative conclusion, it appears that larger mass removal rates are required if a wider range of acceptable test section conditions is to be made available through the suction technique. The relatively low rates of flow through the perforated nozzle wall in the present case were selected with the hope of minimizing flow disturbances in the main stream, but Figs. 6 through 12 show that such disturbances did exist at stations downstream of the suction regions. Therefore, if much more of the boundary layer were removed, even stronger flow disturbances should be expected unless a better type of removal were devised. Such configurations as a single slot, etc., come to mind, but it is not at all evident that they would cause less disturbance in the core flow. Perhaps the most effective technique for suppressing disturbances while getting greater mass removal rates is extension of the perforated area, reduction of hole diameter, and increase in number of holes. At the limit this would lead to an all-porous nozzle which would be difficult to cool, and the flow resistance of the smaller passages through the nozzle wall would tend to decrease flow rates per unit area for fixed pressures.

The addition of auxiliary pumping to enhance the flow rate removed by suction (e. g., an ejector) is not appealing if it adds to the total mass flux to be pumped by the main tunnel pumping system. Such an addition could be avoided by diverting the (sucked) secondary and ejector primary flows through a separate exhaust system, but operating costs would be increased. However, auxiliary pumping on the suction areas appears to be one way to obtain the boundary-layer removal rates needed for broader control of nozzle test section conditions. Nevertheless, that alone would not assure a satisfactory result.

Another approach to solving this problem would involve acceptance of some finite flow disturbances in exchange for larger removal rates and an attempt to design so that the stronger disturbances would not enter the test section. It is not immediately obvious that this would lead to an acceptable solution either.

There was only small effect on diffuser performance regardless of amount or mode of mass removal through the porous walls. This does not seem surprising in view of the small mass flux and the low energy of the removed mass. Tank pressure, p_t, which is more directly important than diffuser efficiency in Tunnel M operation, rose somewhat when suction was applied, as indicated in Table IV. Presumably, this reflects the loss of momentum of the portion of the flow drawn off. In-

creases in tank pressure are undesirable because the pressure ratio driving the nozzle flow is diminished. If larger mass flux were sucked through the nozzle walls and dumped into the tank, it is possible that p_t would rise to unacceptable levels.

SECTION IV
CONCLUDING REMARKS

Satisfactory results were obtained in regard to the basic Mach 12, no-suction nozzle designed as a first step in this investigation. It is possible that replacing the perforated sections of the nozzle with smooth walls would effect further improvement, but the nozzle is entirely acceptable in its present condition. The scope of the study of boundary-layer modulation by suction was not broad enough to warrant major conclusions. The attainment of adequate modulation to permit, say, factors of 4 to 8 variation of test section Reynolds number in a given low-density nozzle flow without changes of boundary-layer thickness causing unacceptable nonuniformity in the inviscid core flow is a desirable goal. However, the results obtained in this brief study suggest that such a level of control cannot be attained without extensive effort toward minimizing flow perturbations in the test section, since even the small rate of mass removal and the rather large area over which it was accomplished caused distortions of the central core flow in the Mach 12 nozzle.

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APPENDIXES

I. ILLUSTRATIONS
II. TABLES

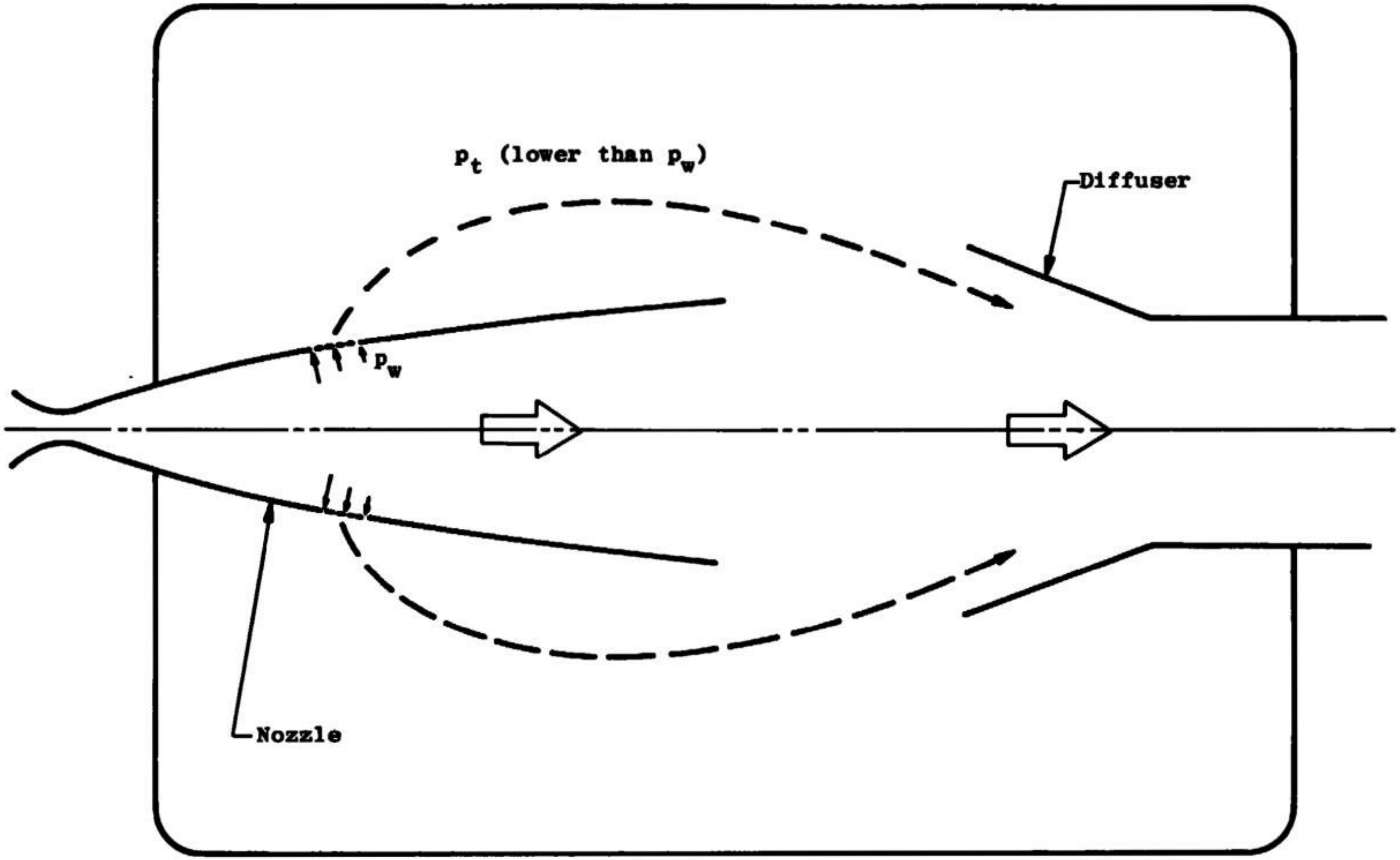
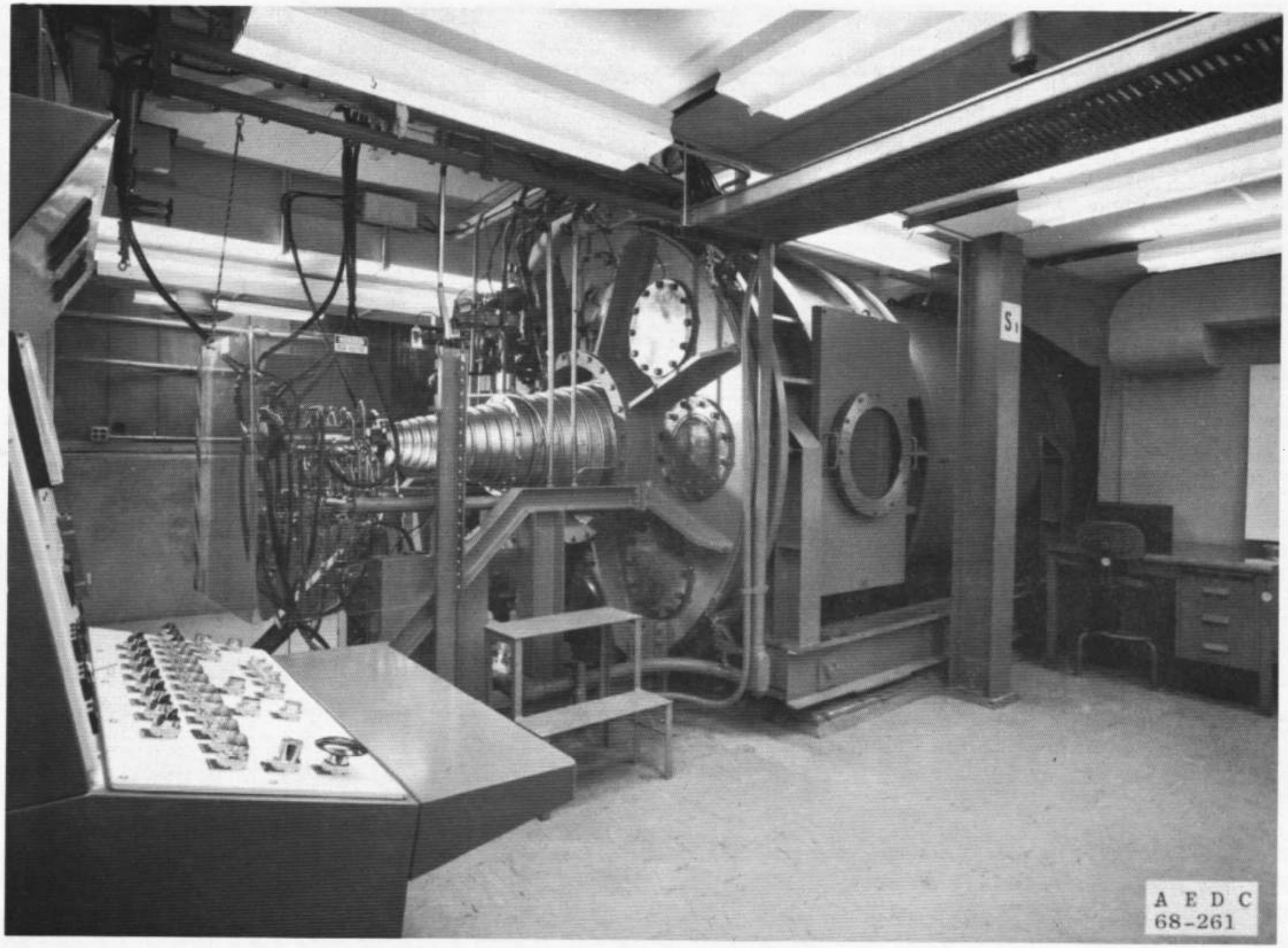
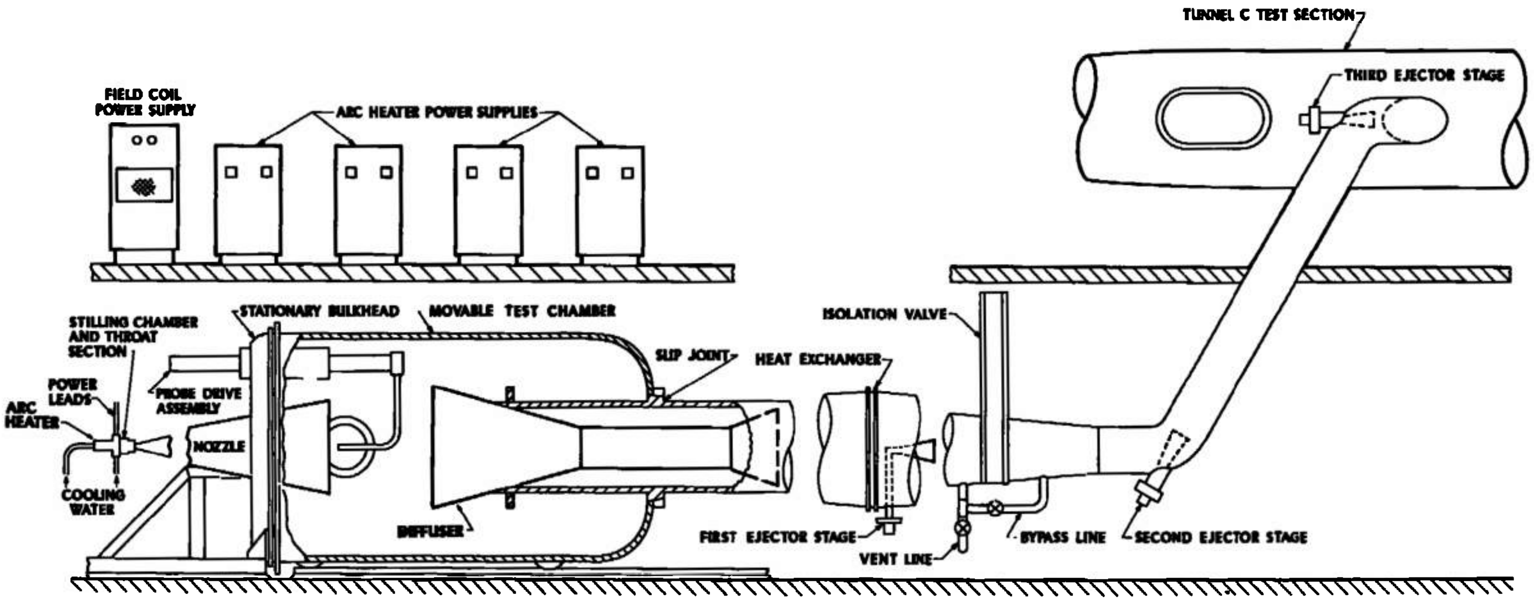


Fig. 1 "Natural" Suction Situation Investigated



a. Photograph of Tunnel M
Fig. 2 Tunnel M



b. Elevation View of Tunnel M
Fig. 2 Concluded

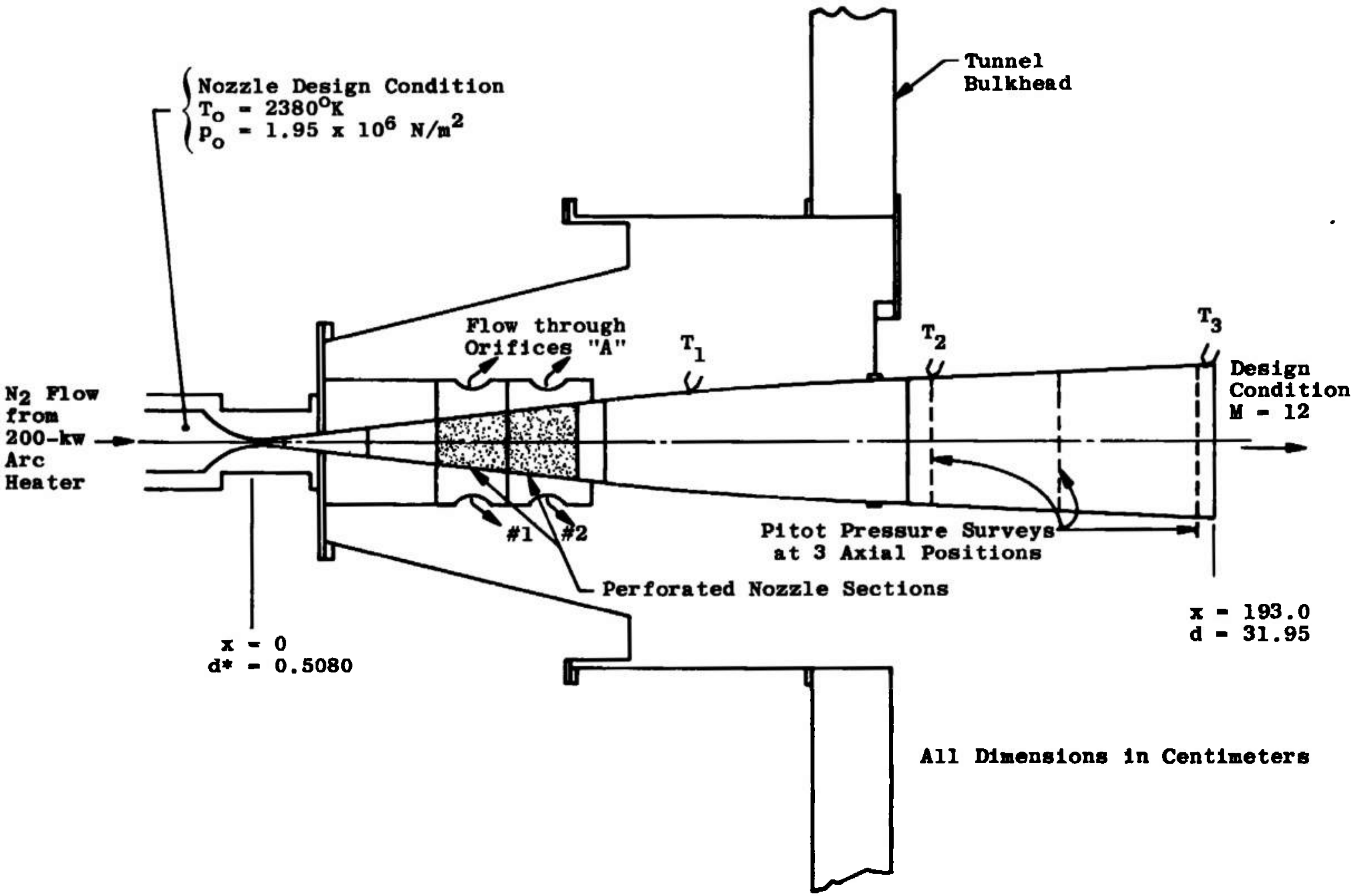


Fig. 3 Porous Nozzle Installation in Tunnel M

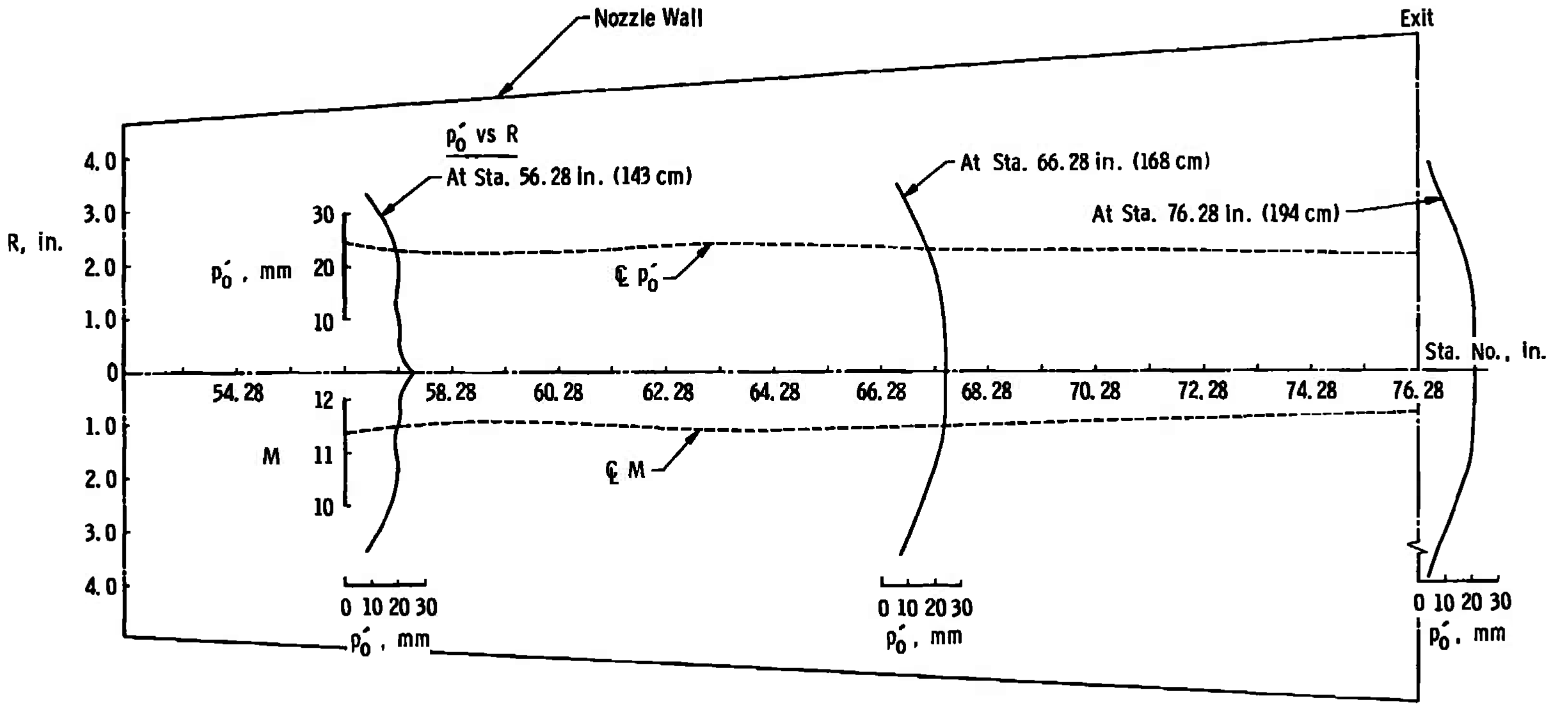


Fig. 4 Impact Pressure Distributions for the Nozzle Design Condition with No Suction

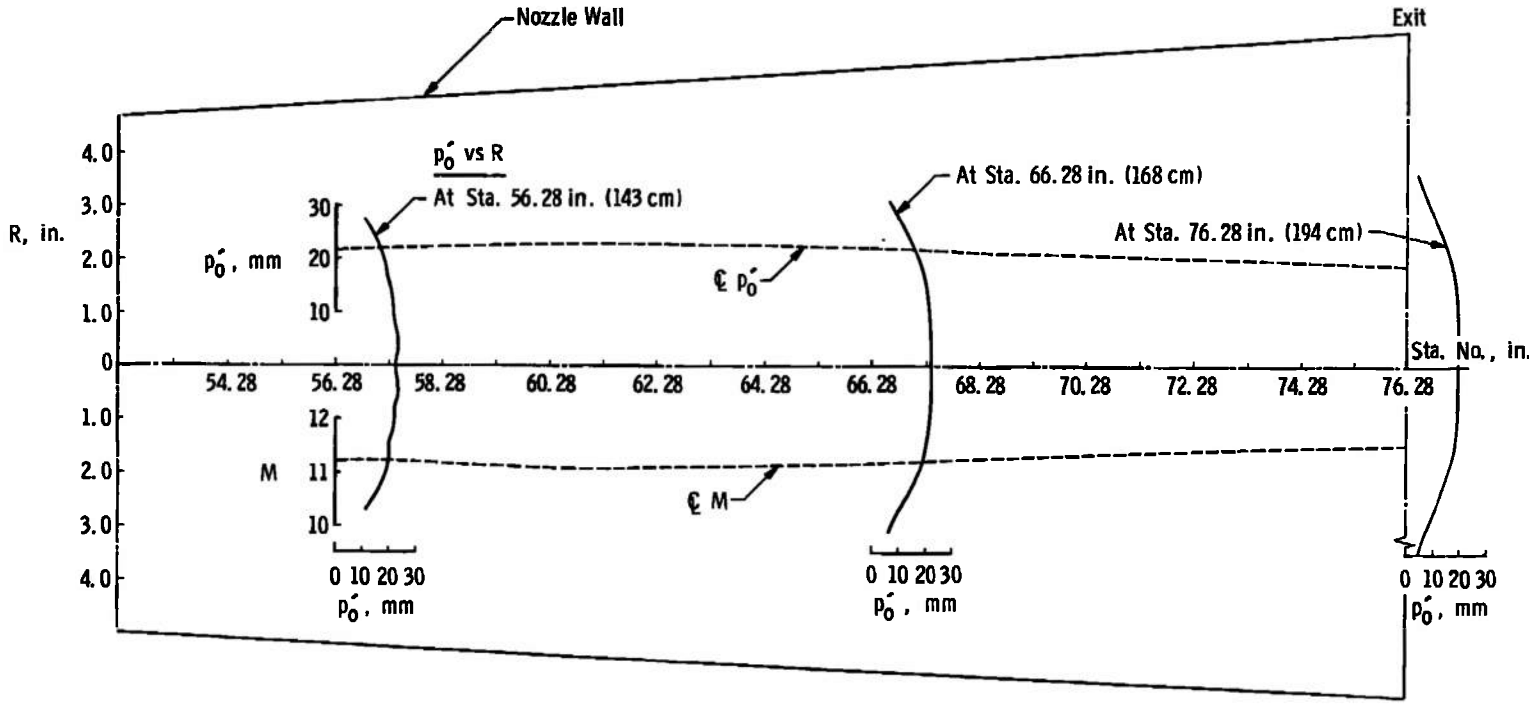


Fig. 5 Impact Pressure Distributions for the Nozzle Off-Design Condition with No Suction

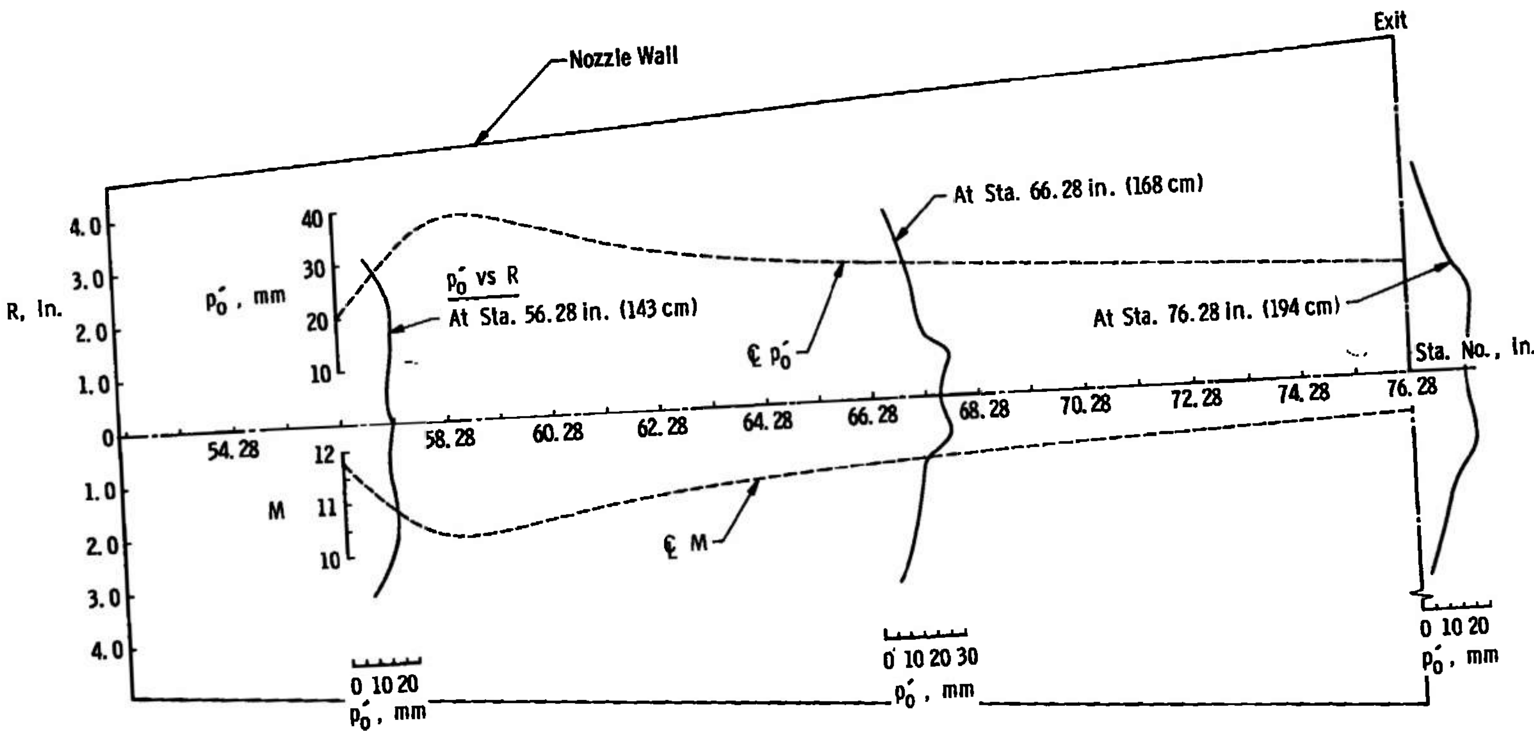


Fig. 6 Impact Pressure Distributions for the Nozzle Design Condition with Full Suction Applied

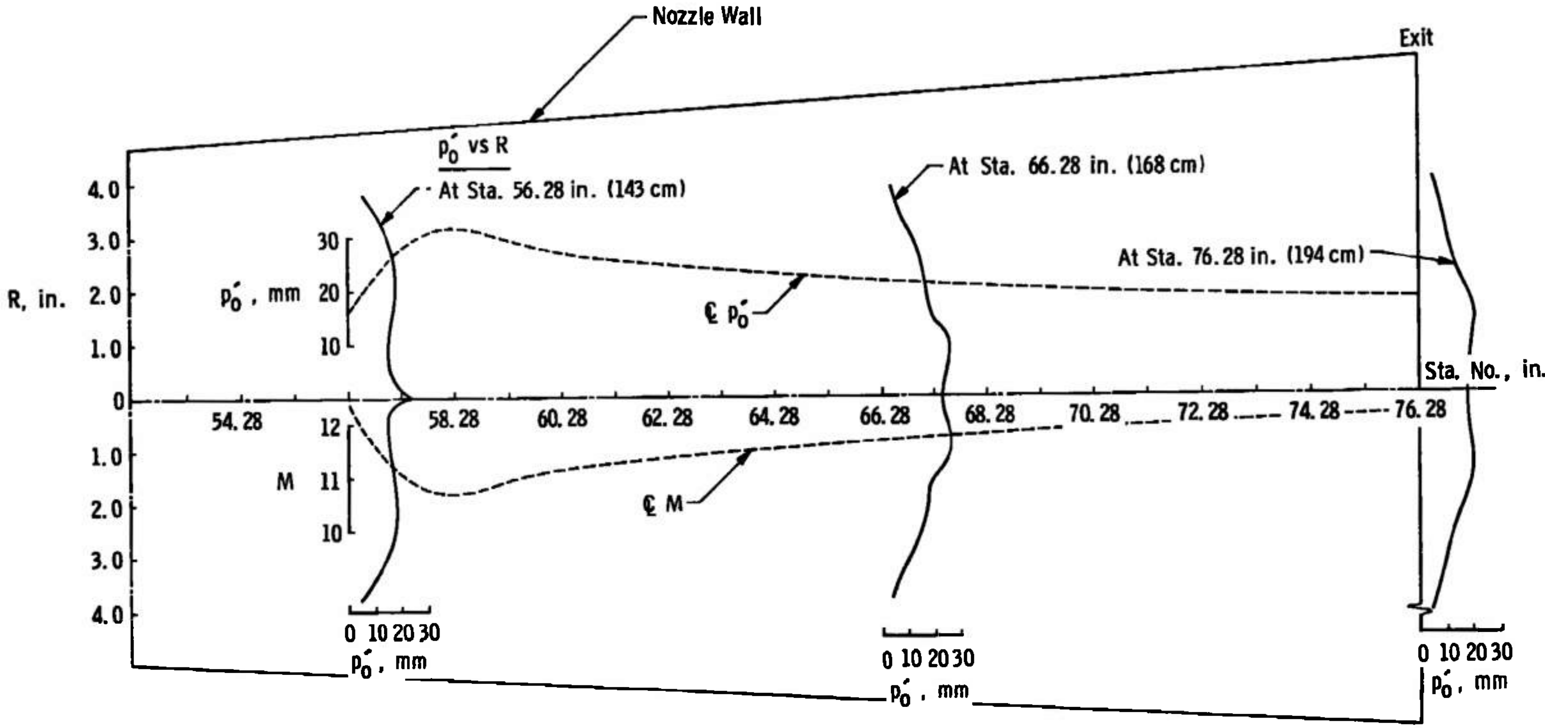


Fig. 7 Impact Pressure Distributions for the Nozzle Design Condition with Full Suction on Section 1 and No Suction on Section 2

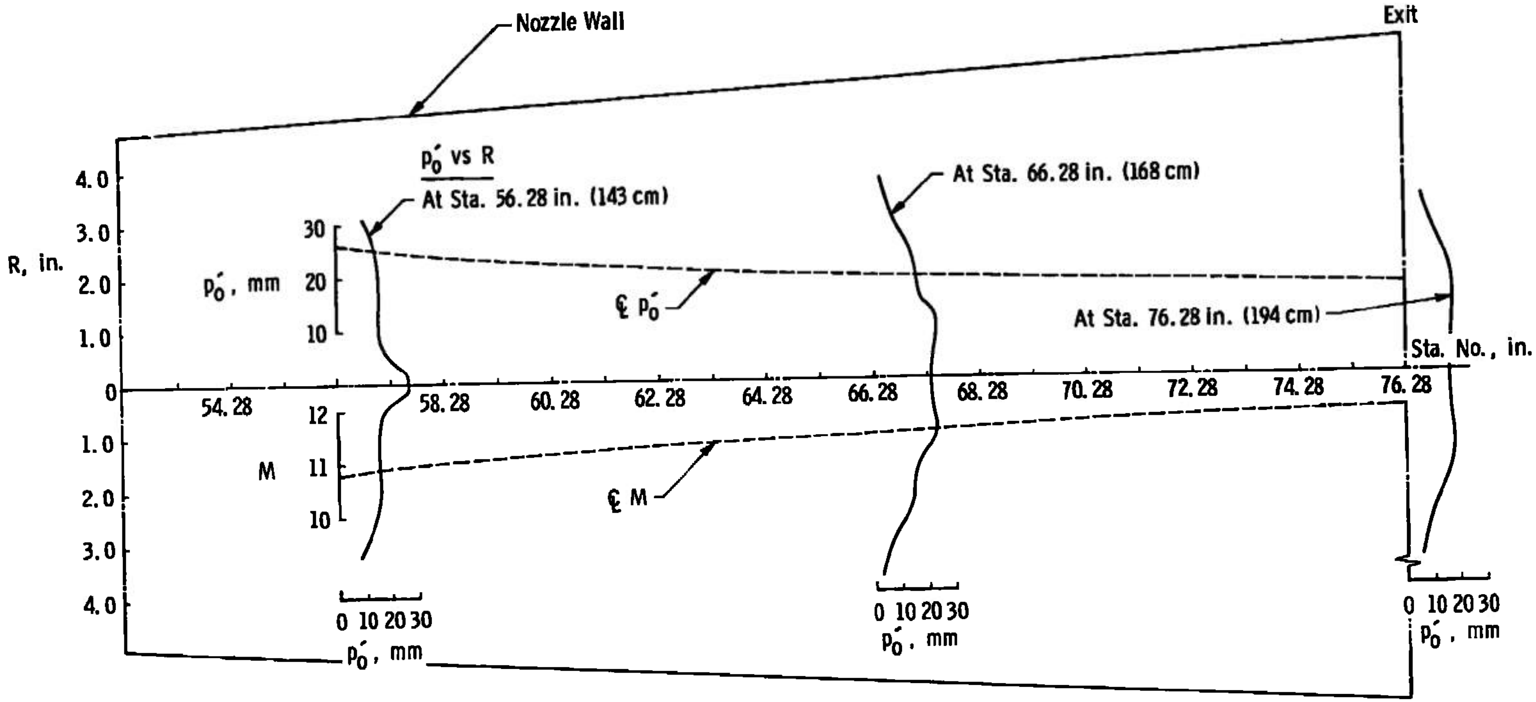


Fig. 8 Impact Pressure Distributions for the Nozzle Off-Design Condition with Full Suction on Section 1 and No Suction on Section 2

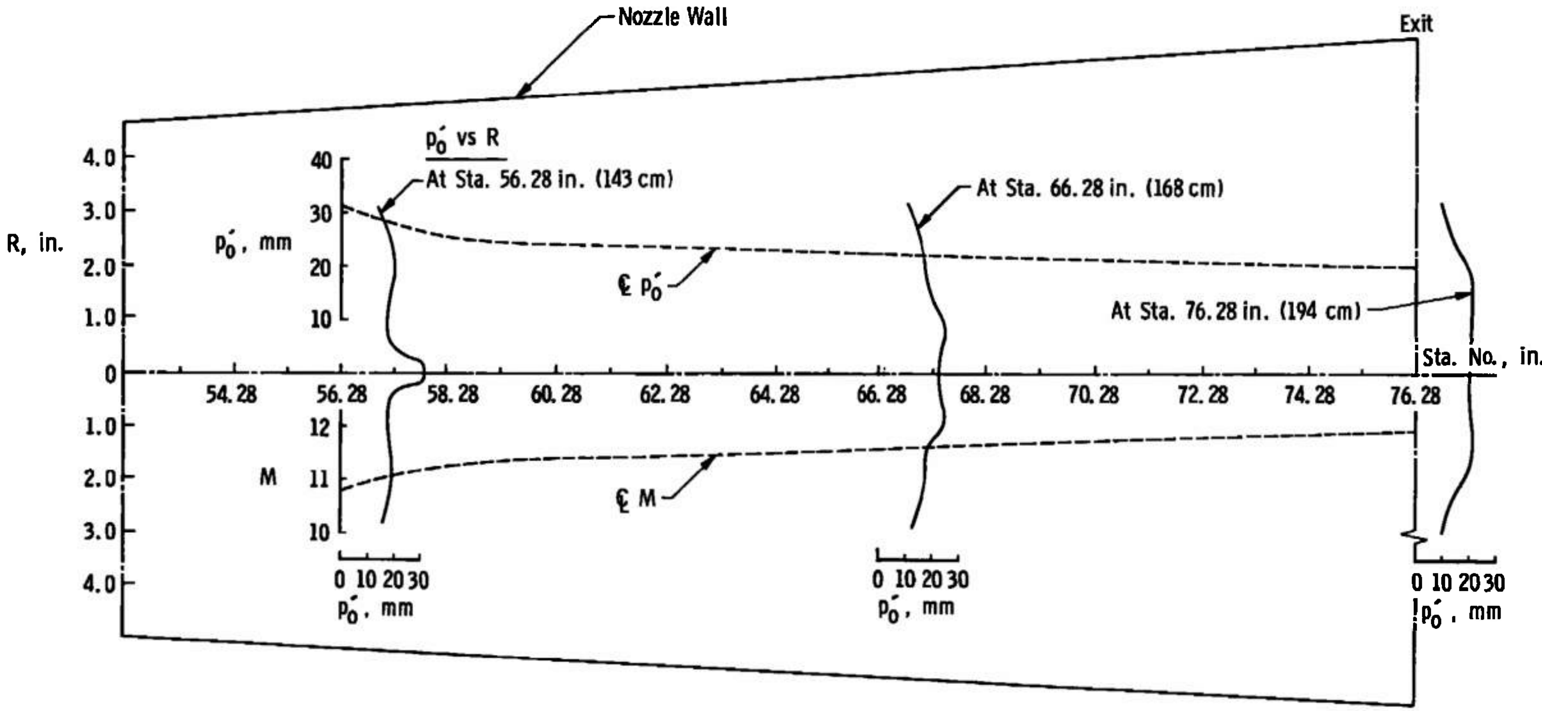


Fig. 9 Impact Pressure Distributions for the Nozzle Design Condition with 68 Percent Suction Rate on Section 1 and No Suction on Section 2

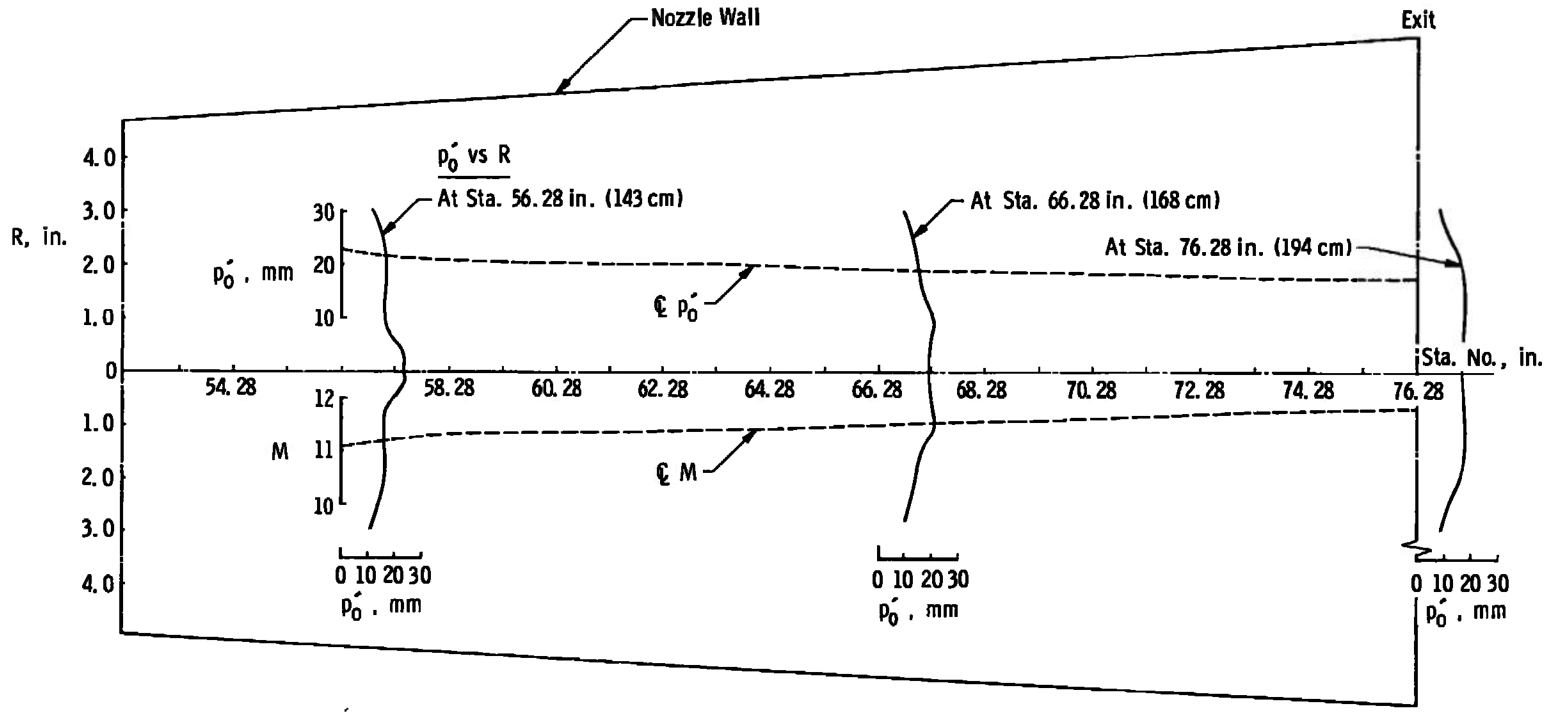


Fig. 10 Impact Pressure Distributions for the Nozzle Off-Design Condition with 70 Percent Suction Rate on Section 1 and No Suction on Section 2

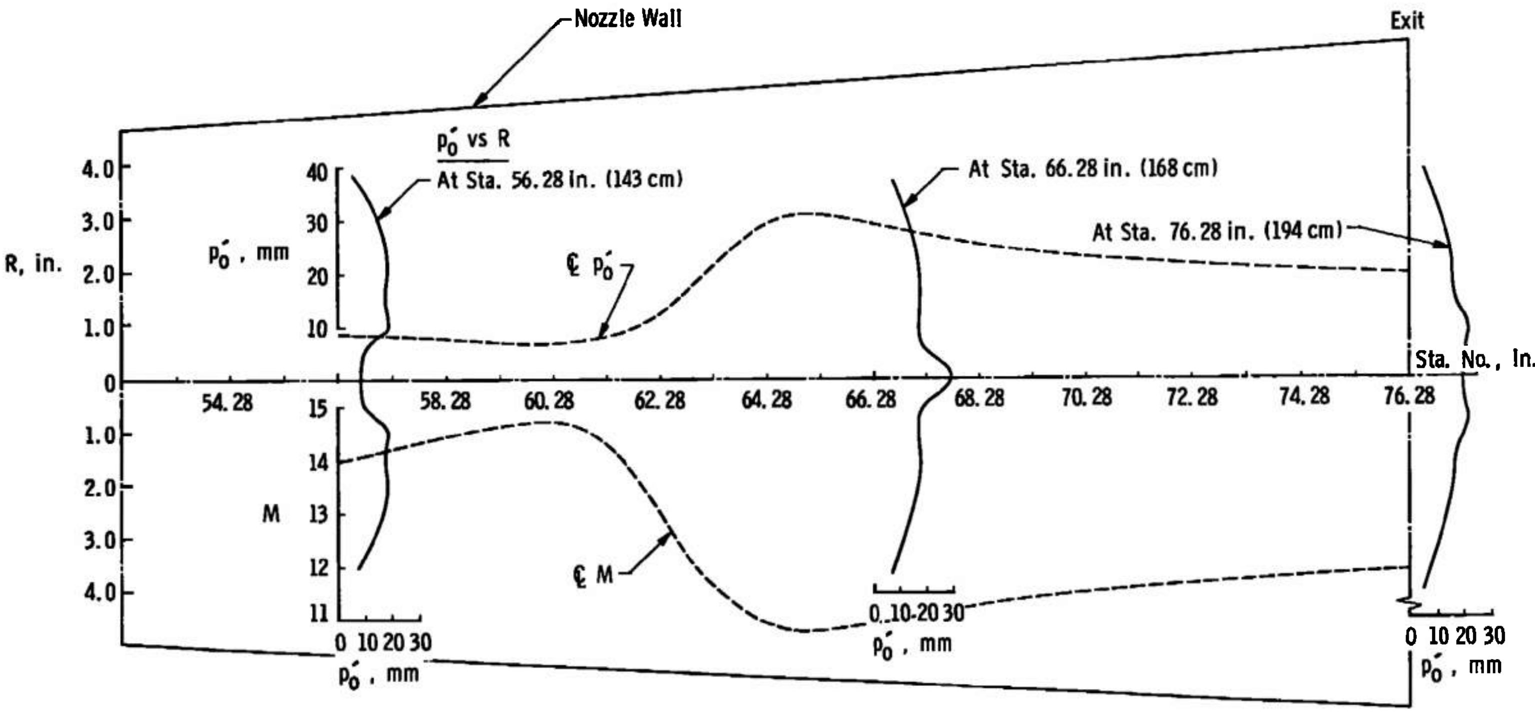


Fig. 11 Impact Pressure Distributions for the Nozzle Design Condition with No Suction on Section 1 and Full Suction on Section 2

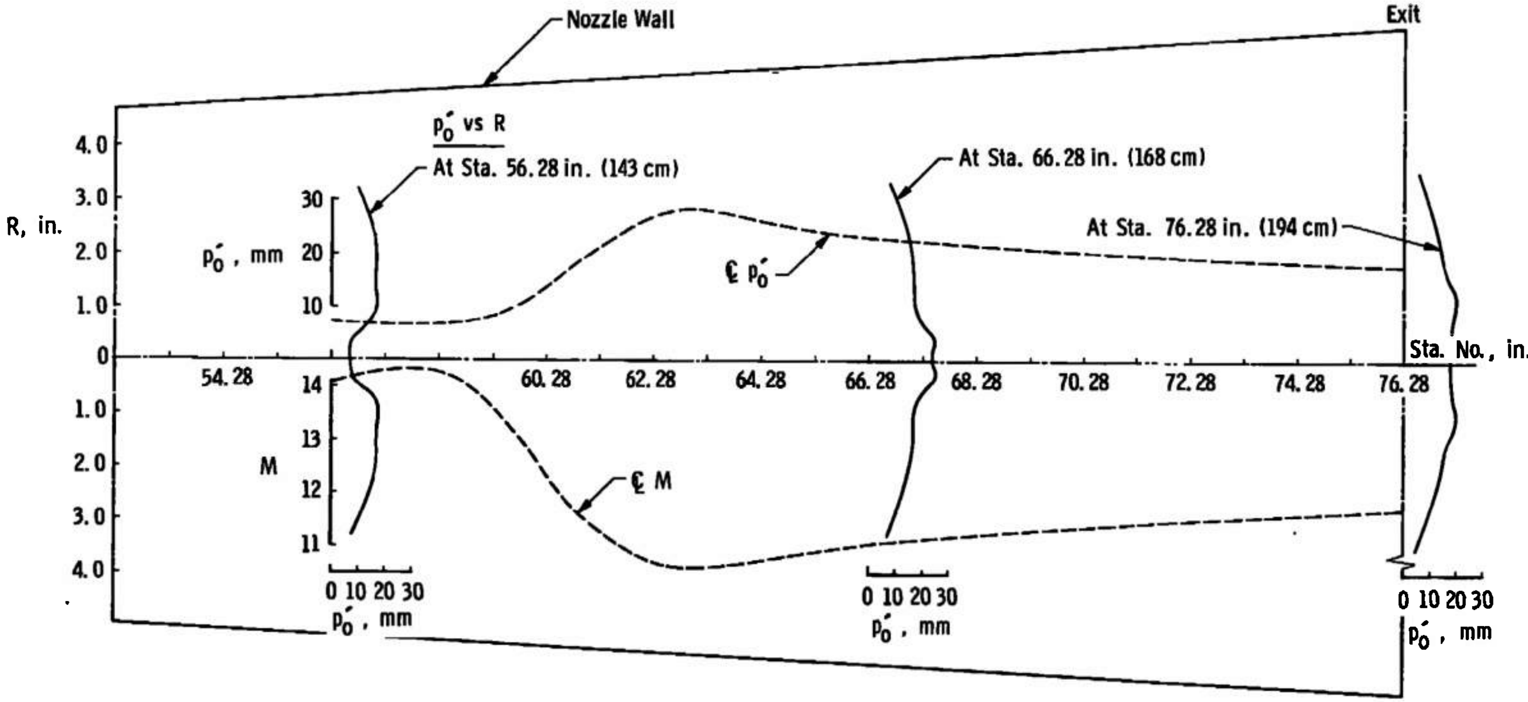


Fig. 12 Impact Pressure Distributions for Nozzle Off-Design Condition with No Suction on Section 1 and Full Suction on Section 2

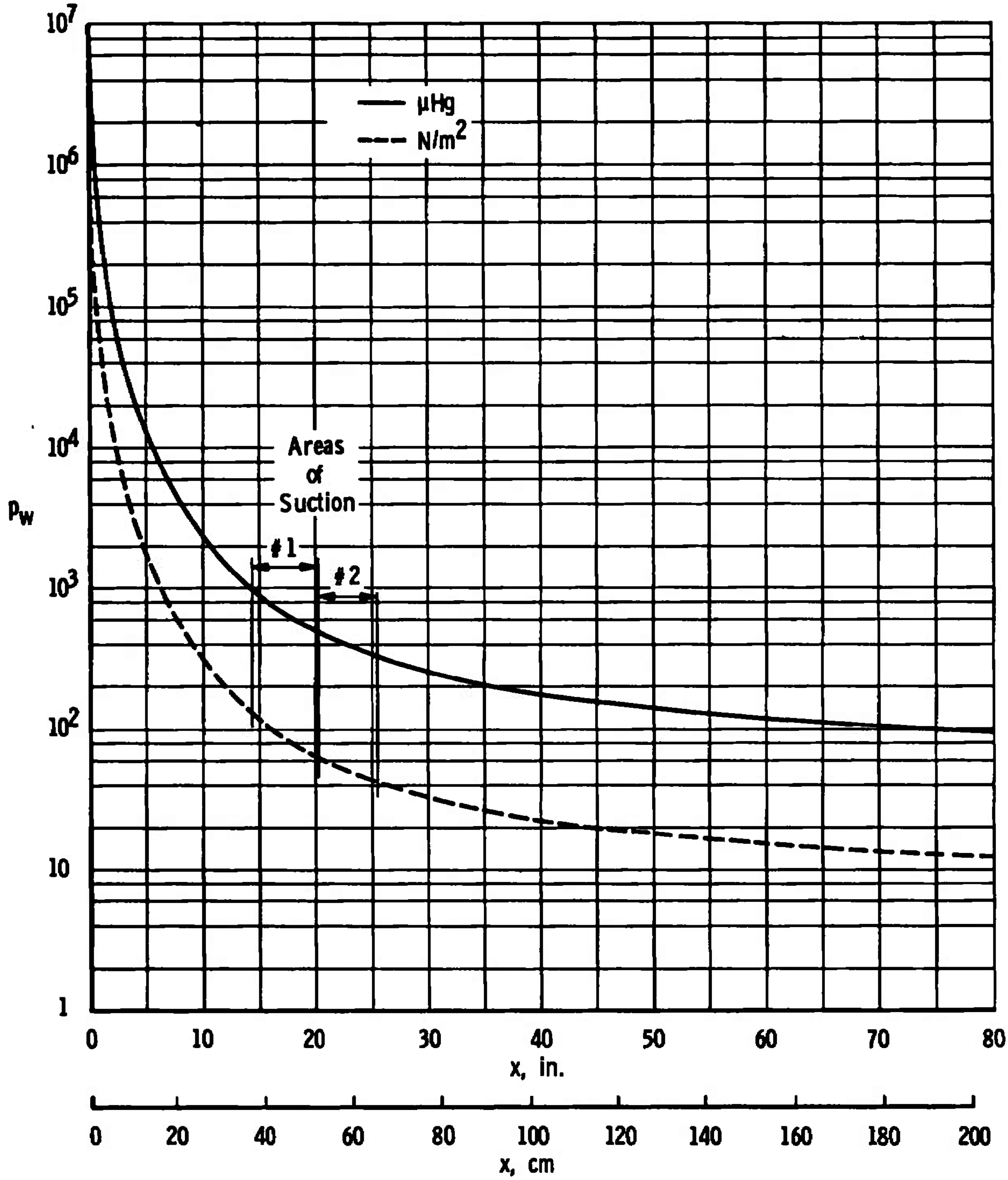


Fig. 13 Computed Distribution of Nozzle Wall Static Pressure

TABLE I
FLOW PROPERTIES AT EXIT OF TUNNEL M MACH 12 CONTOURED NOZZLE: DESIGN CONDITION

Customary Units		SI Units	
p_o, atm	19.26	p_o, N/m^2	1.95×10^6
T_o, °K	2356	T_o, °K	2356
h_o, Btu/lb_m	1194	h_o, J/gm	2780
M_∞	11.83	M_∞	11.83
Re_∞, $in.^{-1}$	5992	Re_∞, m^{-1}	2.36×10^5
p_∞, μ Hg	114	p_∞, N/m^2	15.2
T_∞, °K	84.7	T_∞, °K	84.7
U_∞, ft/sec	7285	U_∞, m/sec	2210
ρ_∞, lb_m/ft^3	3.77×10^{-5}	ρ_∞, kg/m^3	6.03×10^{-4}
λ_∞, in.	2.98×10^{-3}	λ_∞, m	7.57×10^{-5}
q_∞, lb_f/ft^2	31.1	q_∞, N/m^2	1490
$\dot{R}e_2$, $in.^{-1}$	474	Re_2, m^{-1}	1.87×10^4
S_∞	9.9	S_∞	9.9

TABLE II
FLOW PROPERTIES AT EXIT OF TUNNEL M MACH 12 CONTOURED NOZZLE: OFF-DESIGN CONDITION

Customary Units		SI Units	
p_o, atm	16.06	p_o, N/m^2	1.63×10^6
T_o, °K	3026	T_o, °K	3026
h_o, Btu/lb_m	1573	h_o, J/gm	3670
M_∞	11.54	M_∞	11.54
Re_∞, $in.^{-1}$	3677	Re_∞, m^{-1}	1.45×10^5
p_∞, μHg	112.7	p_∞, N/m^2	15.0
T_∞, °K	114	T_∞, °K	114
U_∞, ft/sec	8259	U_∞, m/sec	2320
ρ_∞, lb_m/ft^3	2.76×10^{-5}	ρ_∞, kg/m^3	4.42×10^{-4}
λ_∞, in.	4.74×10^{-3}	λ_∞, m	1.20×10^{-4}
q_∞, lb_f/ft^2	29.3	q_∞, N/m^2	1405
Re_2, $in.^{-1}$	326	Re_2, m^{-1}	1.29×10^4
S_∞	9.65	S_∞	9.65

TABLE III
NOZZLE BOUNDARY-LAYER PARAMETERS

Nozzle Mach No.	T_w/T_o	$(\delta\ \exp/r_w)_{exit}$	δ^*/δ Ref. 2	δ^*/δ experiment	$\frac{\delta^*/\delta \text{ experiment}}{\delta^*/\delta \text{ Ref. 2}}$
18.15	0.10	0.69	0.94	0.72	0.77
11.83	0.13	0.76	0.87	0.59	0.68[a]
10.15	0.09	0.75	0.76	0.56	0.74
9.30	0.12	0.66	0.76	0.62	0.82
2.00	1.0	0.17	0.32	0.29	0.91

[a]As explained in the text, for the actual $\overline{T}_w$ = 390°K and $\overline{T}_w/T_o$ = 0.17, the values of δ^* and δ from Ref. 2 would be increased such that the ratio in this column would increase to roughly 0.7.

TABLE IV
SUMMARY OF RESULTS WITH VARYING MASS REMOVAL RATES

Nozzle Condition	p_1, μHg	p_2, μHg	p_t, μHg	T_1, °K	T_2, °K	T_3, °K	$\dot{m}_1$, lb_m/sec	$\dot{m}_2$, lb_m/sec	$\dot{m}_{tot}$, lb_m/sec	M_{exit}
DESIGN										
No Suction	715	446	35	426	389	352	0	0	0.071	11.83
Full Suction	303	198	45	325	316	308	0.0019	0.0012	0.071	11.90
Suc No. 1 only	306	408	44	315	304	300	0.0019	0	0.071	12.09
Suc No. 2 only	696	208	40	315	305	300	0	0.0012	0.071	11.92
Suc No. 1 only 1/2 open	415	433	48	442	376	346	0.0013	0	0.071	11.95
OFF-DESIGN										
No Suction	673	424	19	462	402	366	0	0	0.054	11.54
Suc No. 1 only	254	367	31	413	348	328	0.0027	0	0.054	11.91
Suc No. 2 only	653	176	29	387	348	326	0	0.0018	0.054	11.76
Suc No. 1 only 1/2 open	355	363	32	358	339	321	0.0019	0	0.054	11.88

μHg x 0.128 = N/m^2

lb_m x 453.6 = grams

UNCLASSIFIED
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13. ABSTRACT
The potential value of controlled boundary-layer removal from the wall of a nozzle for low-density hypersonic flow was investigated in a brief experimental program. A particular objective was the achievement of sufficient control over boundary-layer thickness to enable a contoured "design-point" nozzle to be operated under off-design conditions without excessive deterioration of flow uniformity. The conditions of flow were such that the nozzle contour was greatly influenced by boundary-layer thickness. The manner of boundary-layer fluid removal involved suction through perforated walls by utilization of the naturally available pressure ratio existing where local nozzle static pressures exceeded the pressure in the large tank which enclosed the nozzle and test section. Even though mass flux removed was a small percentage of total nozzle mass flux, there was an adverse effect on flow uniformity with no significant gain in flexibility of usable operating conditions. Although only a short time was devoted to the investigation, it does not appear easy to gain sufficient control over the boundary layer without creating unacceptable disturbances to the test section flow. Some possibilities for gaining boundary-layer control are briefly discussed, but their merits are uncertain. It is obvious that the boundary layer can be removed, but the quality and level of control of the resulting test section flow that can be had for reasonable cost are not equally clear.

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